Reconnection Scaling Experiment (RSX)
3D movies of magnetic reconnection in linear geometry at LANL

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The physics of magnetic reconnection is a major unsolved issue in MagnetoHydroDynamics (MHD). Magnetic reconnection plays a fundamental role in many astrophysical and laboratory plasmas that change magnetic field topology. Magnetic flux annihilates and transforms into plasma kinetic energy - a process beyond the scope of ideal MHD, where magnetic fields are “frozen-in” to the plasma fluid frame. The Reconnection Scaling Experiment (RSX) at LANL can scale between collisional and collisionless reconnection regimes. We will generate 3D movies of magnetic reconnection from many repetitive shots as the reconnection region sweeps down a 4 meter plasma column. We are extending the pioneering work of Stenzel and Gekelman beyond electron MHD to full MHD with magnetized ion flows. We take advantage of the inexpensive and reliable plasma gun technology developed at the University of Wisconsin to generate high density ($>10^{14}$cm^{-3}) high current (J≈300A/cm^2) ohmically heated (T_e>15eV) channels. We model the experiment with 3D fluid simulations (NIMROD) and particle simulations of the reconnection region. This approach represents synergistic collaborations across divisions within the LANL community and has a substantial student participation.

Magnetic Reconnection Scaling Experiment - *RSX*

LANL: P-24 & T-15

production

Laboratory Directed Research & Development - new start FY2000

Univ. of Wisconsin

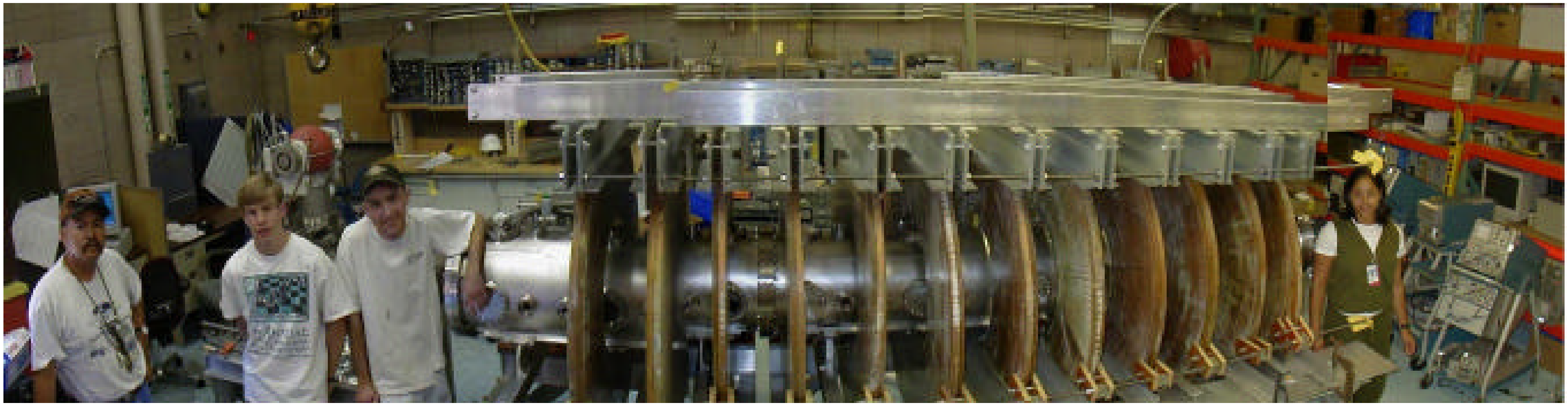
Collaboration

APS-DPP

23-27 Oct 2000

Quebec City, Canada

RSX and protagonists



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RSX

• The physics of magnetic reconnection is a major unsolved issue in MagnetoHydroDynamics (MHD).

• Magnetic reconnection plays a fundamental role in many astrophysical and laboratory plasmas that change magnetic field topology.

• Magnetic flux annihilates and transforms into plasma kinetic energy, which is beyond the scope of ideal MHD, where magnetic fields are "frozen-in" to the plasma fluid frame

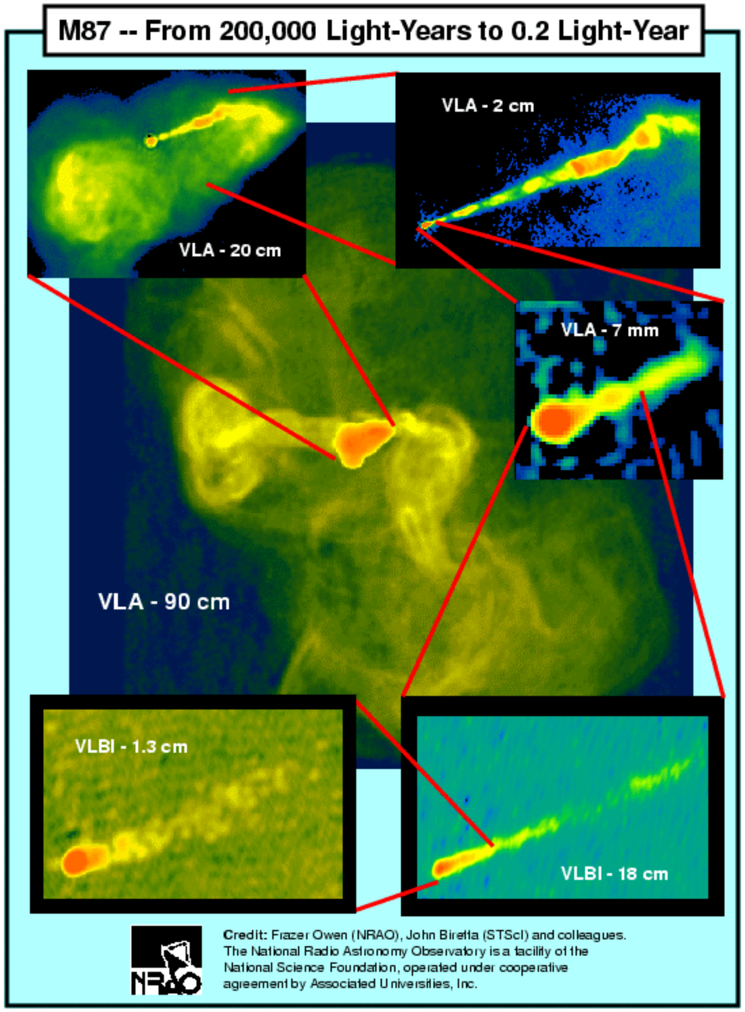
• 3D movies with detailed diagnostics will have a large impact on our first principles understanding of magnetic reconnection in the solar corona, the Earth's magnetosphere and astrophysical plasmas, as well as practical implications for satellite communication and magnetically-confined fusion.

RSX can scale between resistive MHD and collisionless reconnection regimes

- *Experiment* … LANL P-24:
  - PI Intrator
  - Students: Werley, Lasley, Calloway, Reynolds
  - Technician: Begay, Barela
  - Univ. Wisc plasma gun technology: Fiksel
  - 3D movies of experimental data

- *Model simulations: LANL*
  - NIMROD 3D 2 fluid, boundary: Sovinec T-15

Galactic jets - powered by reconnection?



Magnetic Diffusion

Maxwells equations

Take the curl

$$\times B = \mu_0 J + \partial D / \partial t$$

$$\times E = -\partial B / \partial t$$

$$\times(\quad \times B) = \mu_0 \quad \times J + \partial D / \partial t$$ *(neglect displacement current)*

add resistivity to MHD description for a moving frame

$$E + \mathrm{v} \times B = \eta J$$

diffusion equation for magnetic field

$$(\eta / \mu_0) \quad {}^2 B + \quad \times (\mathrm{v} \times B) - \quad (\eta / \mu_0) \times (\quad \times B) = \partial B / \partial t$$

diffusion Frozen flux Resistivity gradients

Ohm's Law

$$-m_e/e\, d\mathbf{V}_e/dt = (\mathbf{E}+\mathbf{U}\times\mathbf{B}) - \eta\mathbf{J} - \mathbf{J}\times\mathbf{B}/n_e e + \nabla P_e/n_e e + \nabla\cdot\Pi_e/n_e e$$

electron inertia	Ideal MHD	res MHD	Hall-whistler	isotropic P	stress tensor
1 c/ω_{pe}	2	3 ν_{ei}	4 c/ω_{pi}	5 ρ_i	6

•rearrangement of the electron momentum equation,

•where $\mathbf{V}_e$ and $\mathbf{U}$ are mean electron and center of mass velocities, $\mathbf{J}/(ne)\approx\mathbf{U}-\mathbf{V}_e$. Terms outside the scope of resistive MHD are labeled 1, 4, 5, and 6.

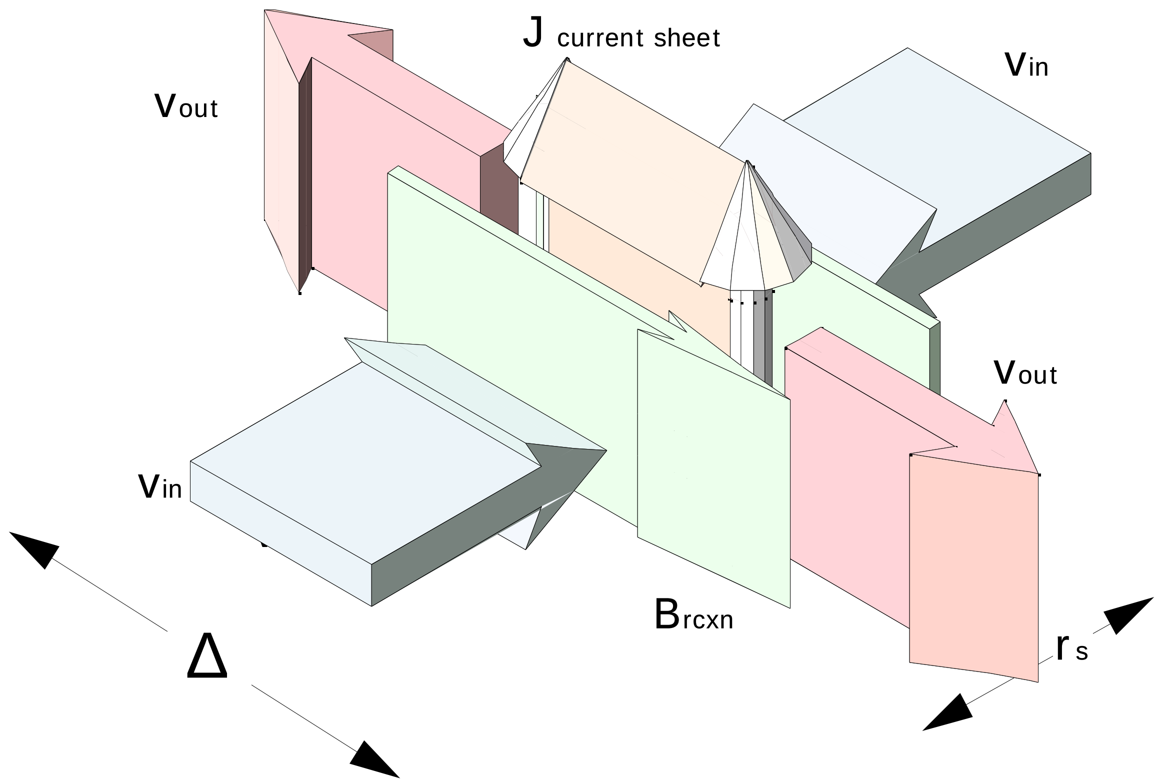
•The term 1 on the left is electron inertia, which yields reconnection on the spatial scale of the electron skin depth $\delta_e=c/\omega_{pe}$.

•Term 4 contains the Hall effect which leads to whistler wave coupling to magnetic perturbations, and it introduces the ion skin depth spatial scale $\delta_i=c/\omega_{pi}$.

•The component of Term 5 parallel to the magnetic field is usually small and does not effect reconnection.

•Term 6 includes kinetic, heat flux and other effects and may be very important for reconnection under some conditions

Current sheet reconnection geometry



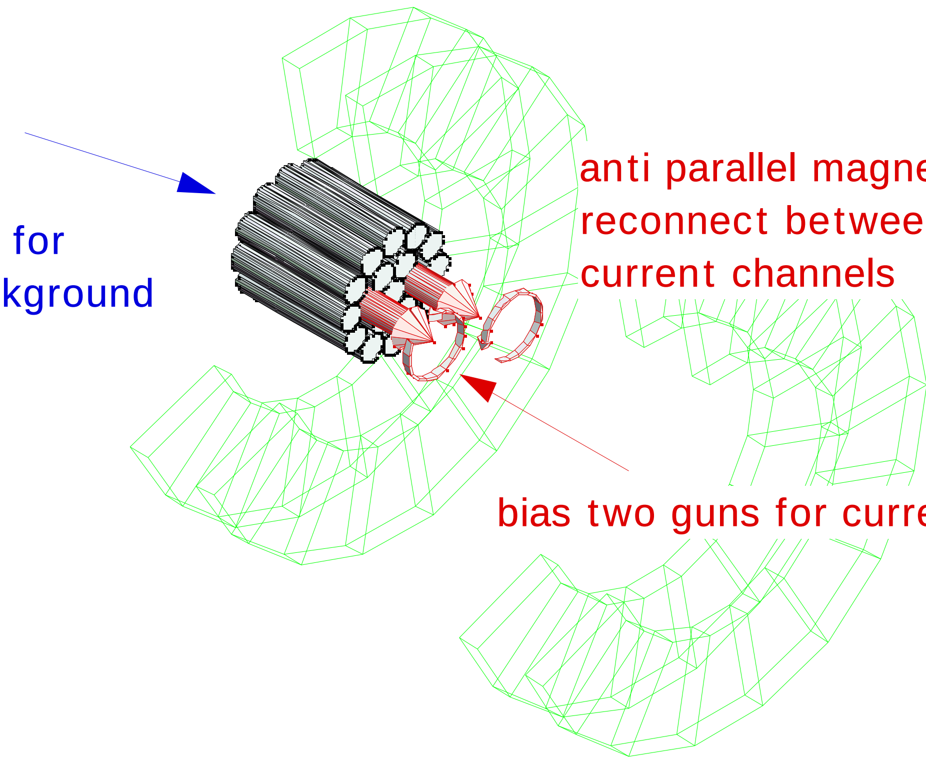
Premise of RSX

- Extend the pioneering results of UCLA groups from Electron Magneto Hydro Dynamics (EMHD) to:
  - Magnetized ions ion MHD
  - Warmer plasma $T_e > 15\text{-}20$ eV
  - Reduced coulomb collisionality
  - Large density $n > 10^{14}\ \mathrm{cm}^{-3}$
  - Reduced Alfven wavelengths, slower Alfven speeds
  - Lundquist number $S >> 1$
- Linear geometry
- Many reproducible shots ($>10^4$)
- Detailed diagnostics showing
  - Fields B, E
  - Particles n, T
  - Waves, correlations

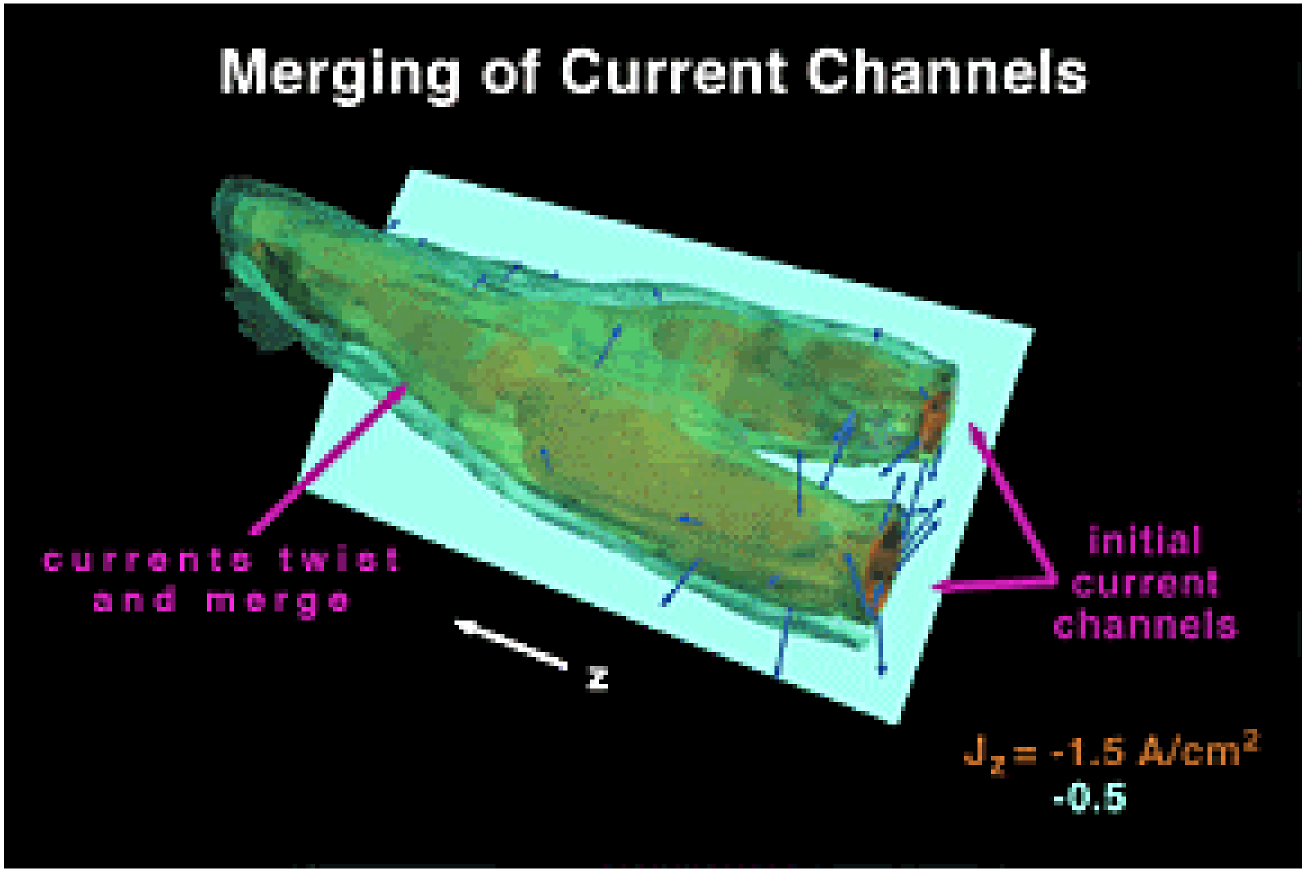
Comparison with several existing experiments

parameter		LAPD rcxn	Stenzel helicity	TS-3 spheromak	MRX	SSX	RSX
resistive time (μs)	$\tau_R = a^2/(\eta/\mu_0)$	150	10	600	200	200	100-600
Alfvén time (μs)	$\tau_A = L/V_A$	230	25	3	<1	<1	0.04-1
reconnection time (μs)	T_{rcxn}	185	100	<30	<10	10	1-10
Lundquist S	$S=\tau_R/\tau_A$	<1	<1	200	300	300	<800
Ion sound gyroradius (cm)	$r_{Gi}=c_s/\omega_{ci}$	20	40	0.5	0.5	0.5	0.1-4
Electron skin depth (mm)	$\delta_e=c/\omega_{pe}$	6	6	0.3-.6	0.3-.6	0.3-.6	0.3-2
ion skin depth (cm)	$\delta_e=c/\omega_{pi}$	24	24	1-2	1-2	2	1-7

Current sheet reconnection geometry



Sample frame from a 3D movie: Data from UCLA EMHD experiments



Gekelman, W., Maggs, J., Pfister, H., *Experiments on the Interaction of Current Channels in a Laboratory Plasma: Relaxation to the Force- Free State*, IEEE Transactions on Plasma Science, V20, N6, 1992.

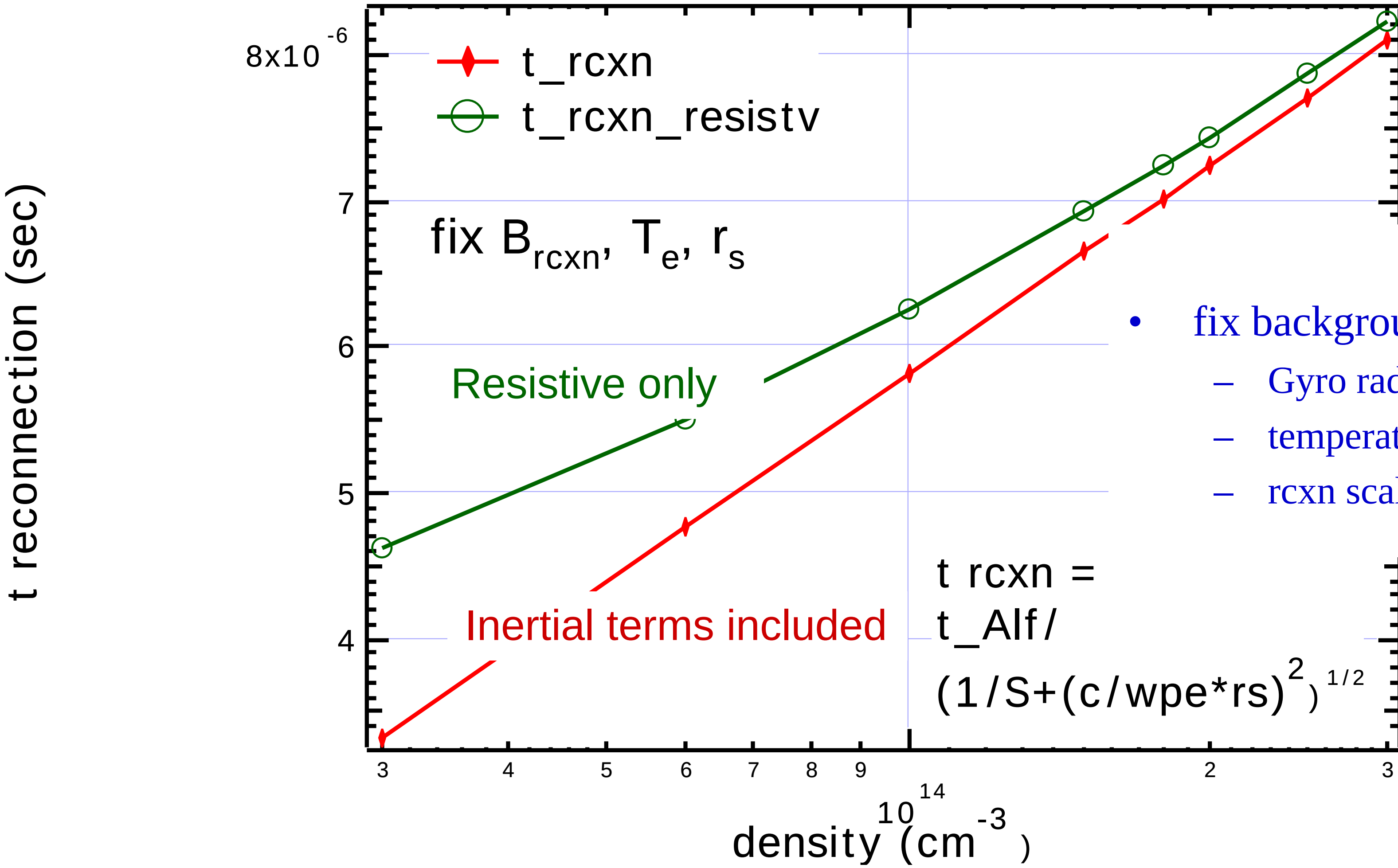
Advantages of RSX?

- Reduce the technology to a minimum to create plasma and current channels
  - Use plasma guns developed by Univ Wisconsin as a commercial solution
- Linear geometry reduces ambiguities of toroidal curvature
- Many key plasma parameters can be directly and independently scaled and are not coupled by force balance, stability, formation issues (viz tokamaks, spheromaks)
- Many ($>10^4$) short (≈100μsec) reproducible pulses are obtainable using plasma guns
  - Make 3D movies for space & time evolution
- Focus efforts instead on diagnostics, physics, data acquisition instead of hardware

Scaling advantages of RSX

- Many key plasma parameters can be directly and independently scaled and are not coupled by force balance, stability, formation issues (compared to *e.g.* tokamaks, spheromaks)
  - Particle gyro radius B field
  - Electron skin depth density
- Beam source relevant to target plasmas can be independently varied
  - Pulse plasma guns into buck or boost magnetic fields
  - Arrays of plasma guns can be assembled to generate beam shapes
    - sheet, round, skewed wrt to each other, lemniscate …

Scale τ_{rcxn} via density scan

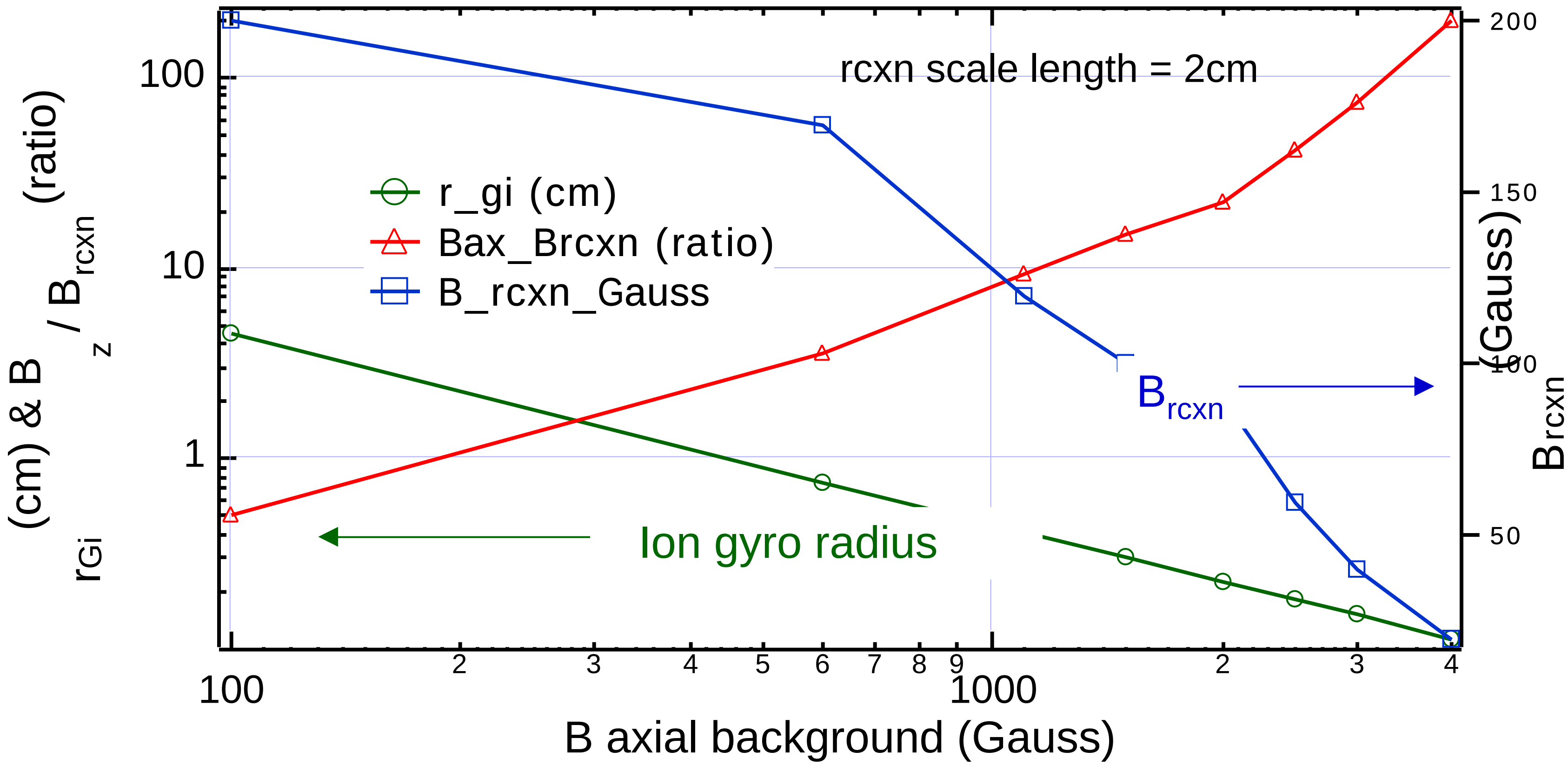


- fix background
  - Gyro radius B_0
  - temperature T
  - rcxn scale length rs

Scaling ion gyro radius

magnetization of ions independent of B_{rcxn}, v_A

- fix rcxn scale length (current channel to channel separation)
- Vary external magnetic field, gyro radius



What about end effects?

- Maximum propagation speed is faster of Alfven or whistler velocities ≈ $3\text{x}10^7$ cm/sec
- A vessel length of 2-4 meters allows time for reconnection evolution before current channel reaches the end of the device
  - $v_A \approx 3\text{x}10^7$ cm/sec
  - $t \approx 400\text{cm}/\ 3\text{x}10^7\ \text{cm/s} \approx 13$ usec
- End effects do not interfere with measurement of reconnection dynamics

Typical Time scales

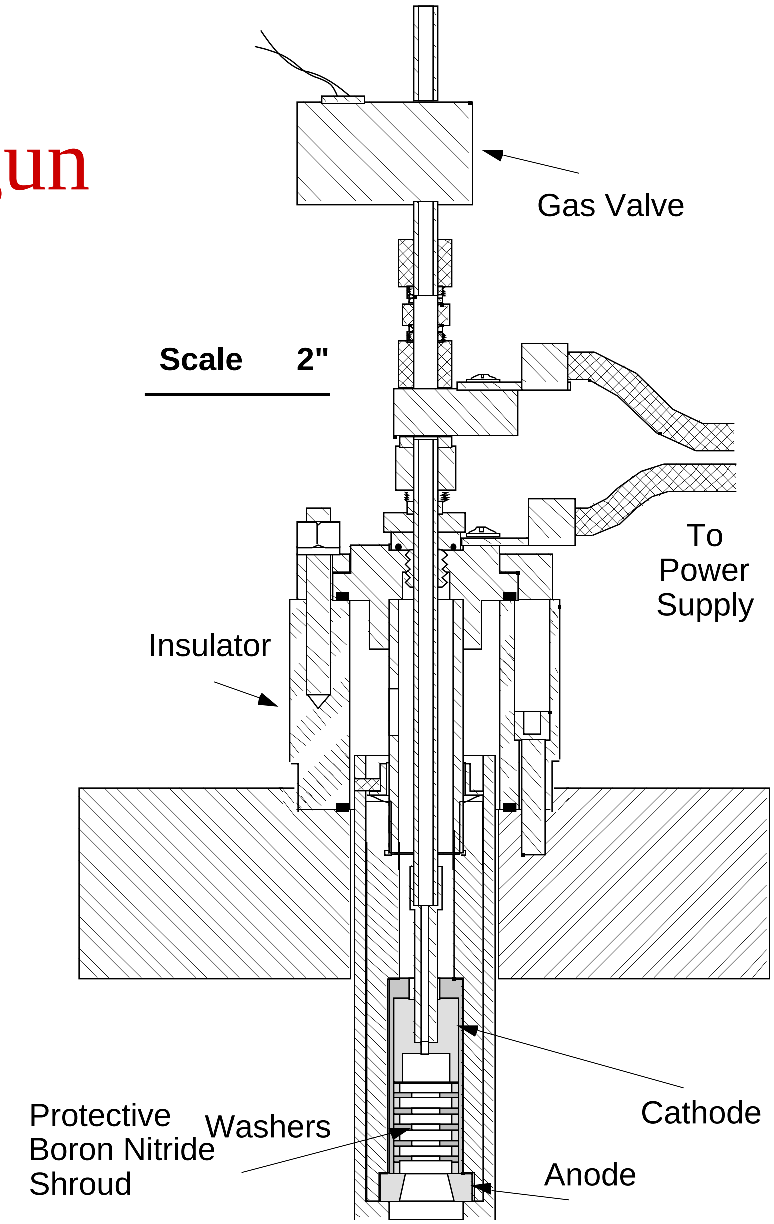
- $\tau_{\text{resistive}} \approx$ msec   resistive flux diffusion
- $\tau_{\text{Alfven}} \approx$ 1-2 μsec   ideal MHD time
- Lundquist number
  - $\tau_{\text{resistive}} / \tau_{\text{Alfven}} \approx$ 200-1000
- $\tau_{\text{transit}} \approx$ 10-15 μsec   down plasma chamber axis

Disadvantages of RSX?

- Non closed (eg toroidal) geometry means that long time scale relaxation processes
  - eg tearing modes
- will take much longer than the transit time between plasma guns and other end of the vacuum chamber
- We wont be able to look at them in RSX

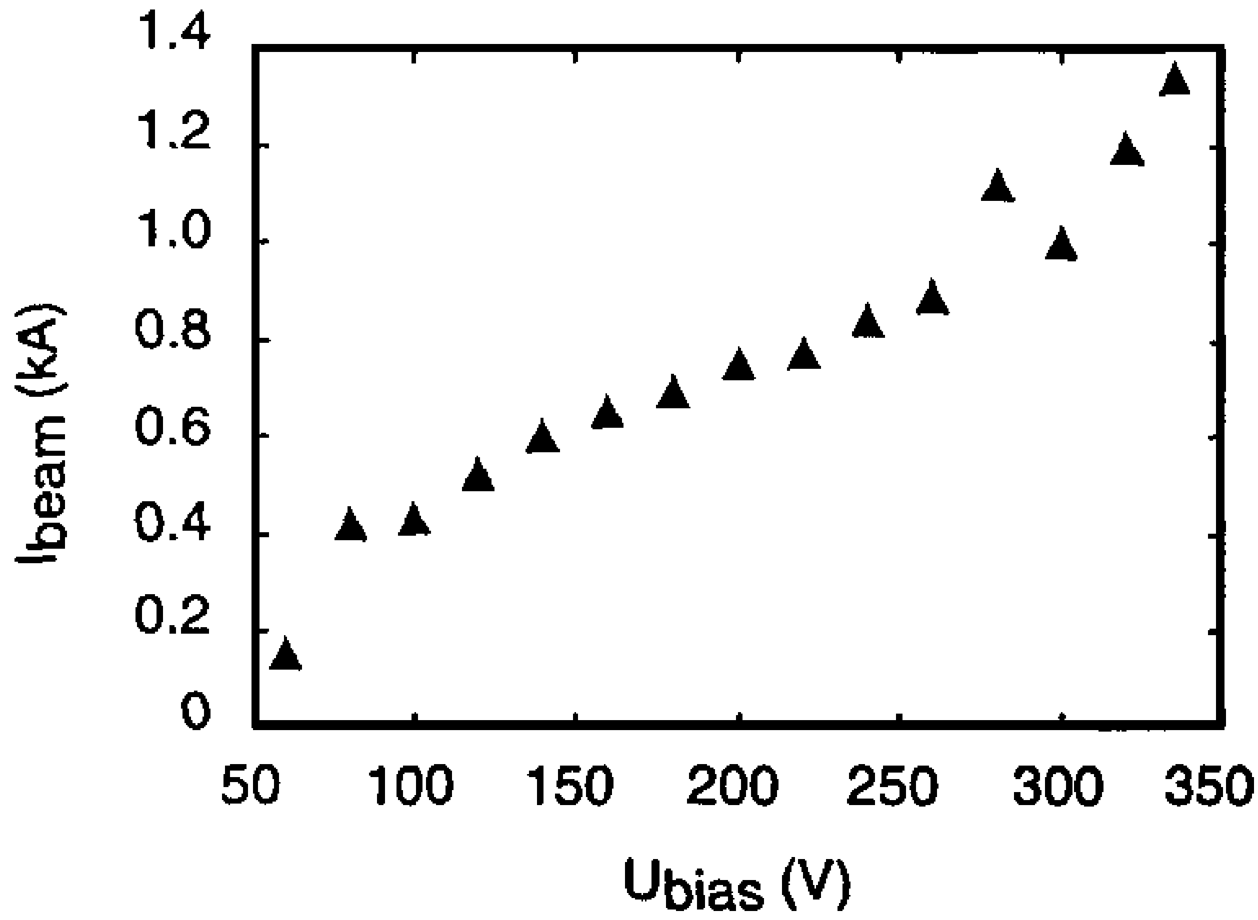
Schematic of plasma gun

- Gas prefill inside gun 2-20psi
- Internal bias strikes arc to anode
- Plasma jet emerges as neutral current
- External bias can yield 100% of this as charged current
- Zeff ≈ 1
- Robust, off the shelf technology

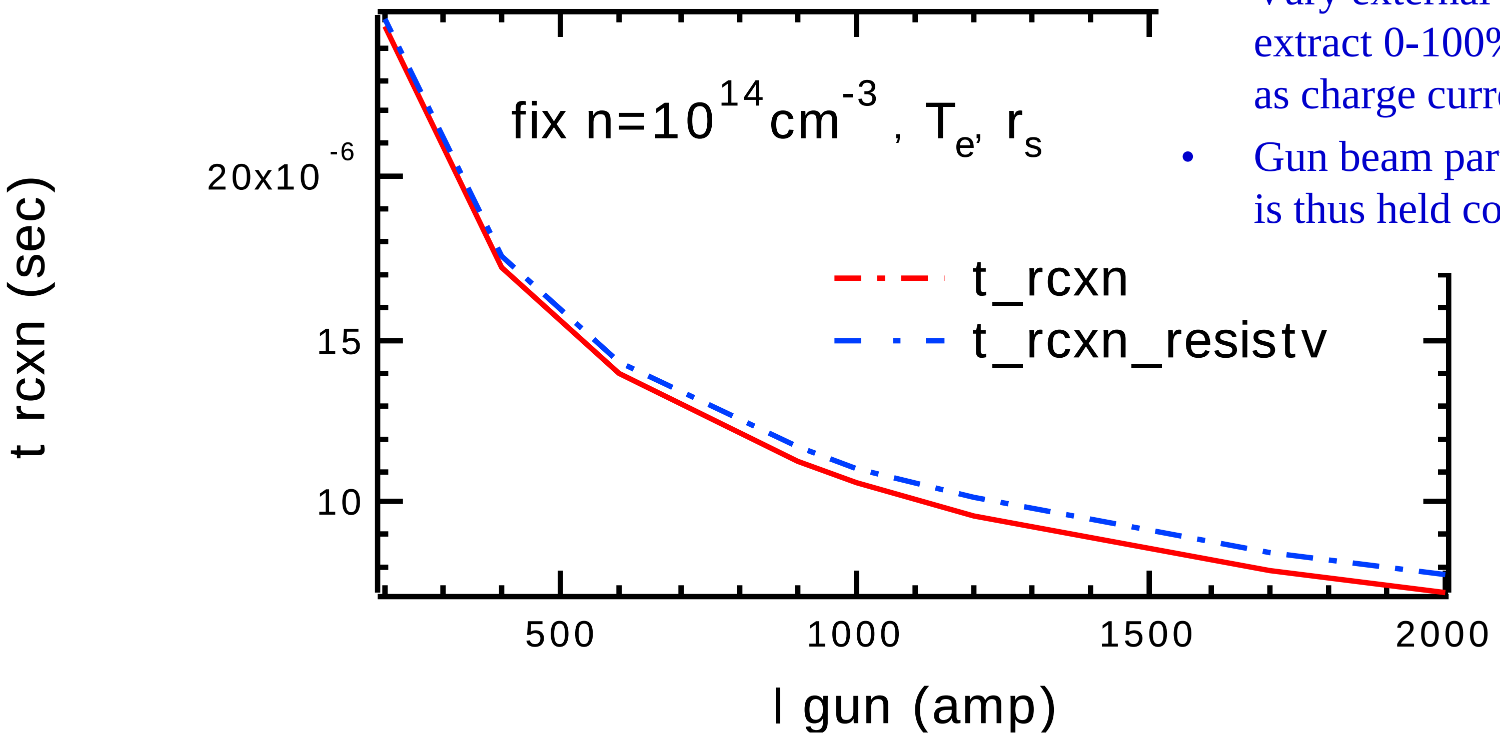


Fixed gun neutral current of 1kA (atomic amp)

External bias voltage determines charged current fraction



Scale τ_{rcxn} via gun current scan



- fix total atomic amps of gun flux with gun prefill pressure
- Vary external gun bias to extract 0-100% of this flux as charge current
- Gun beam particle density is thus held constant

Vary v_A with reconnection B_{rcxn} field

How relevant is the Sweet Parker picture?

- One simplified Sweet-Parker picture includes collisional and collisionless scales:

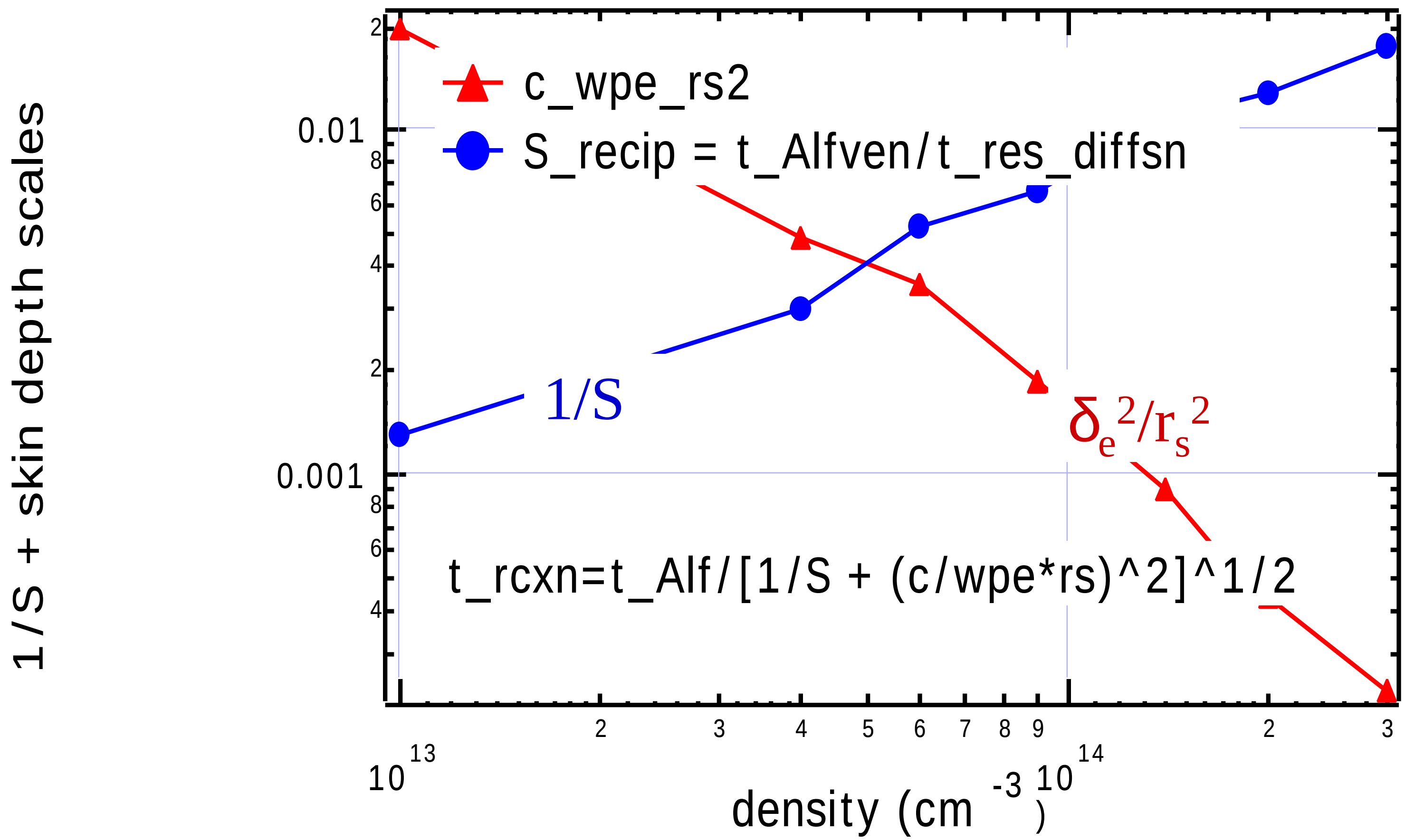
Lundquist number

- $\tau_{rcxn} \approx \tau_A /(\tau_A/\tau_R + \delta_e^2/r_s^2)^{1/2} = \tau_A/(1/S + \delta_e^2/r_s^2)^{1/2}$

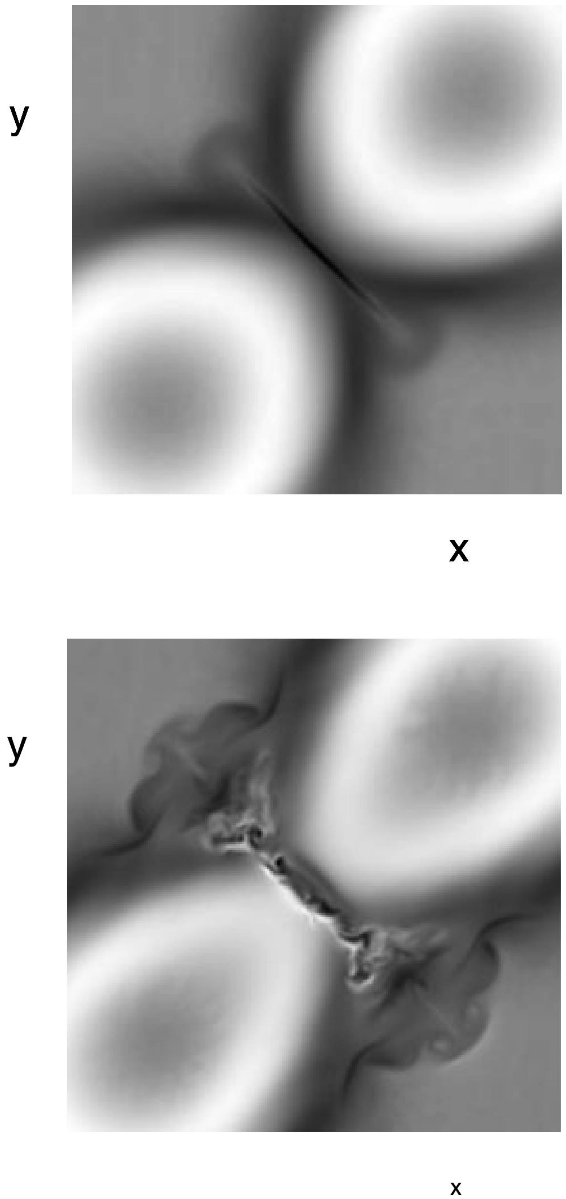
- ideal MHD inertial effects

- A wide range of space and time scales significant for reconnection
- The resistive MHD model predicts that the reconnection time scales with $S^{-1/2}$ for sufficiently large S.
- BUT resistive diffusion competes with the electron inertia - whistler effects, and that for large S plasmas electron inertia effects (whistler and Hall term) control the reconnection and collisions are irrelevant (ie $S^{-1/2}$ scaling does not obtain).
- We can scale the relative sizes of these two terms in RSX easily

Compare:
resistive diffusion (large density)
collisionless reconnection (lower density)



Simulations of 3-D collisionless reconnection



•Narrow electron current layers in the dissipation region break up.

•Too turbulent to even define a current layer,

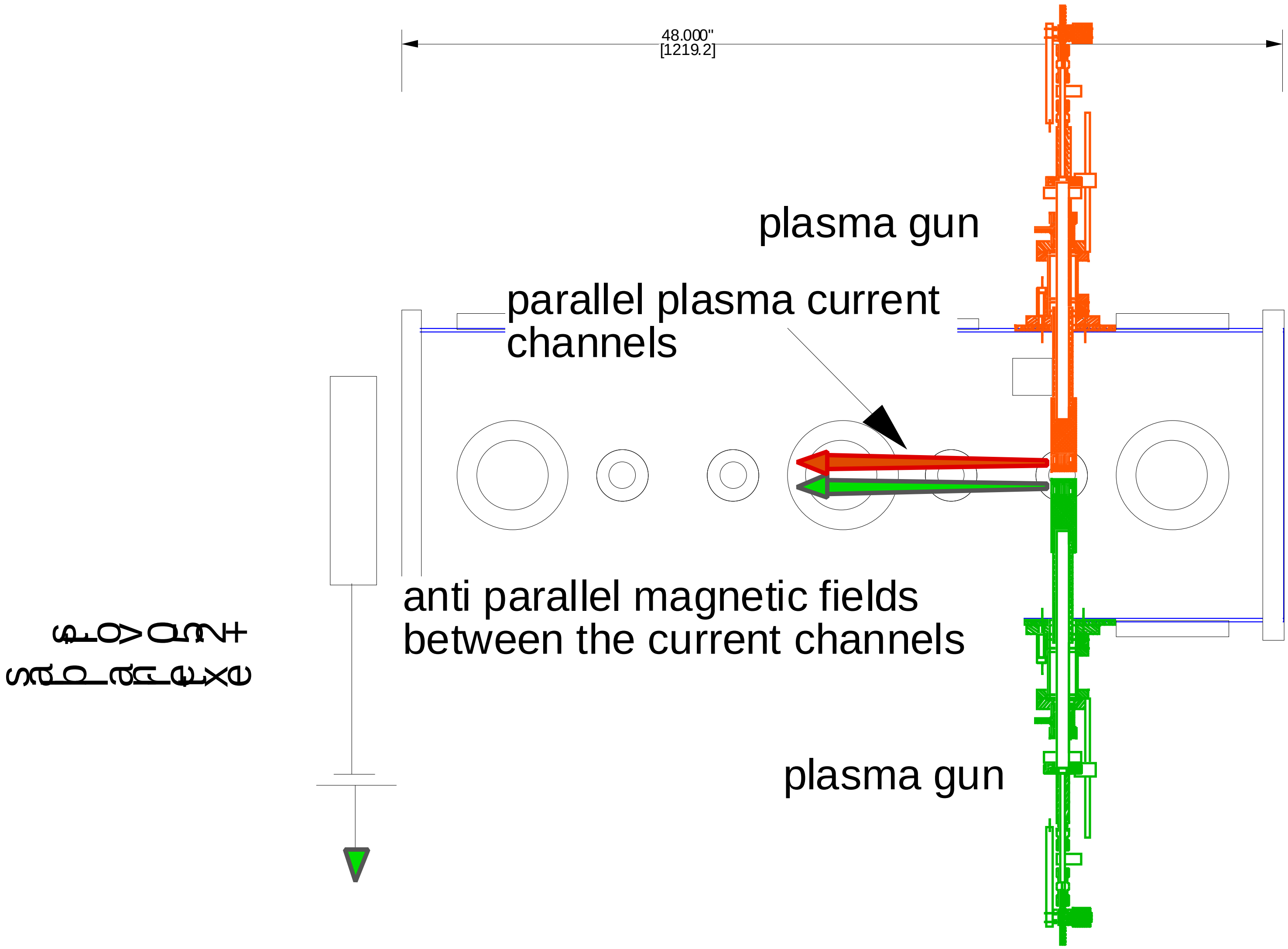
•Current is largely shunted into the plane of the reconnection process.

•Electron inertia is required to break the frozen flux constraint, but the reconnection rate is controlled by the ion dynamics.

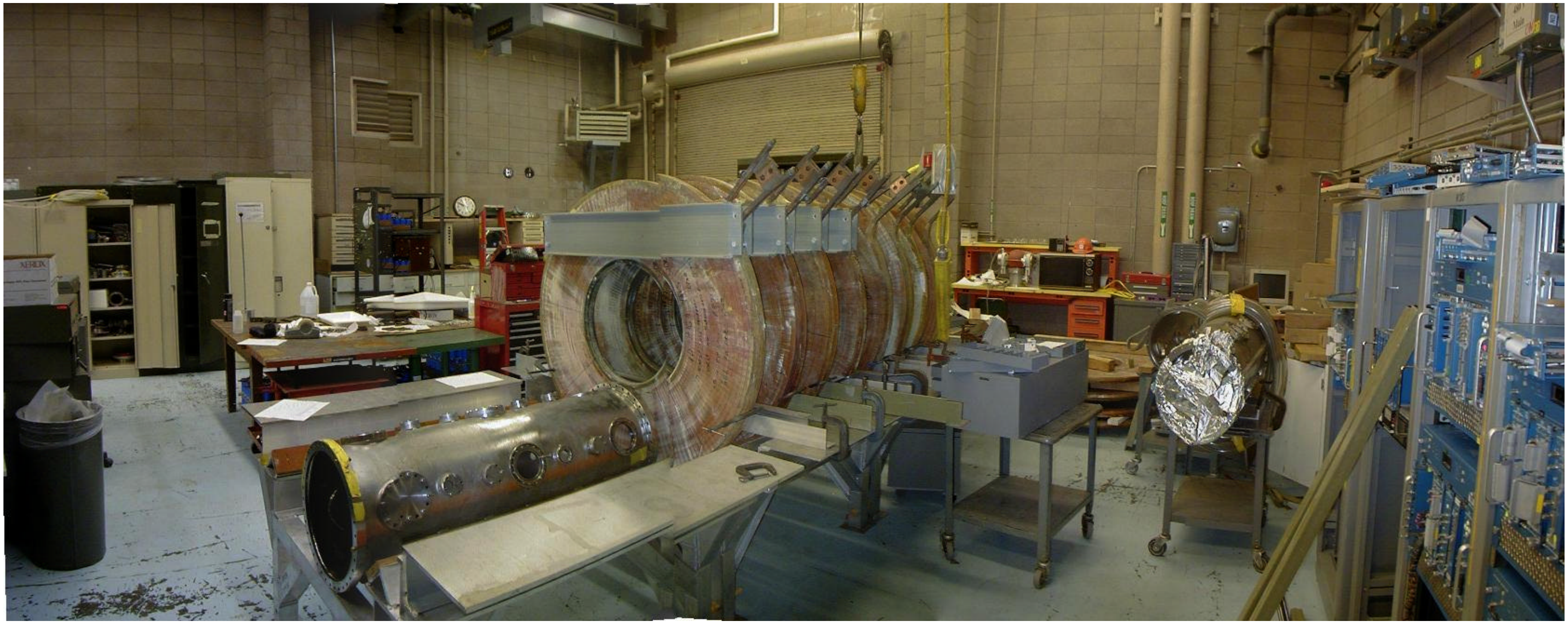
Figure 1. Greyscale plot of the axial current j_z in a region of the $x - y$ plane at $t = 1:0$ in (a) and $t = 1:75$ in (b). Note that the current layer is a region of negative current.

DRAKE ET AL.: 3-D MAGNETIC RECONNECTION, GRL, 24, 2921 (1997)

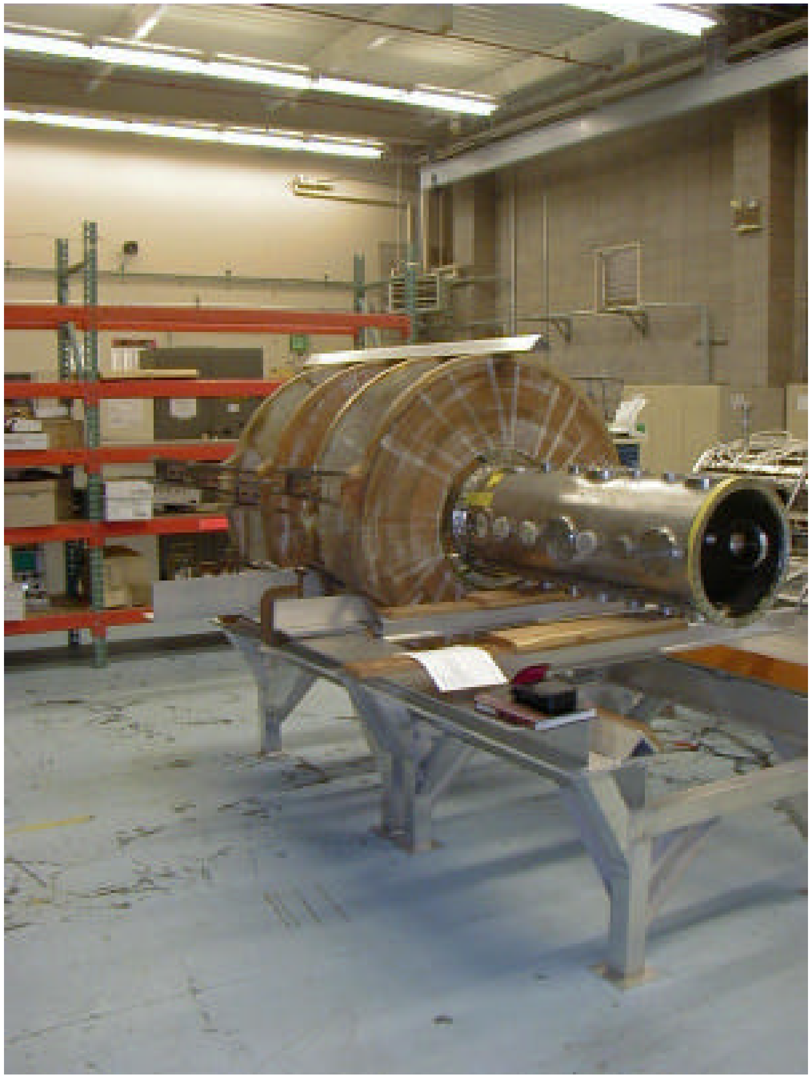
Initial shakedown experiments with 2 plasma guns



A few coils in place



vessel pieces, flanges recycled from FRX-C

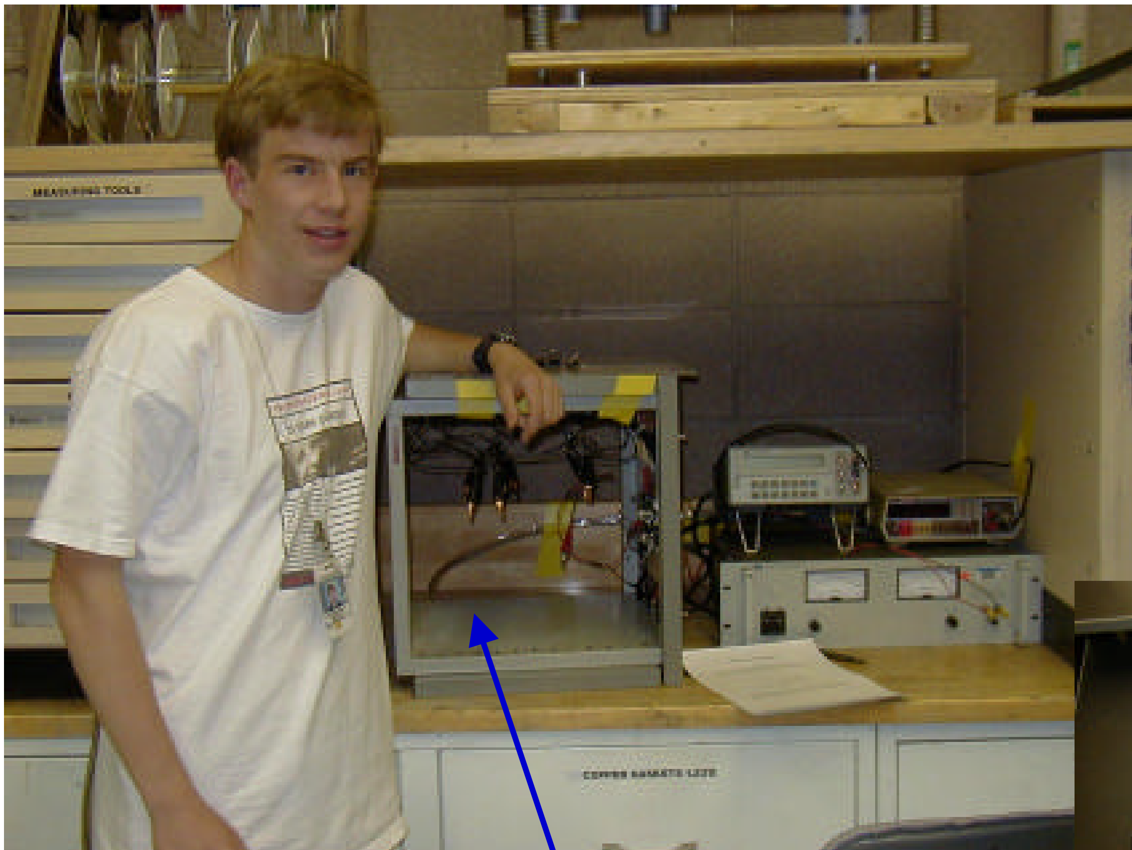


crane into place

Cleaning up recycled vacuum system

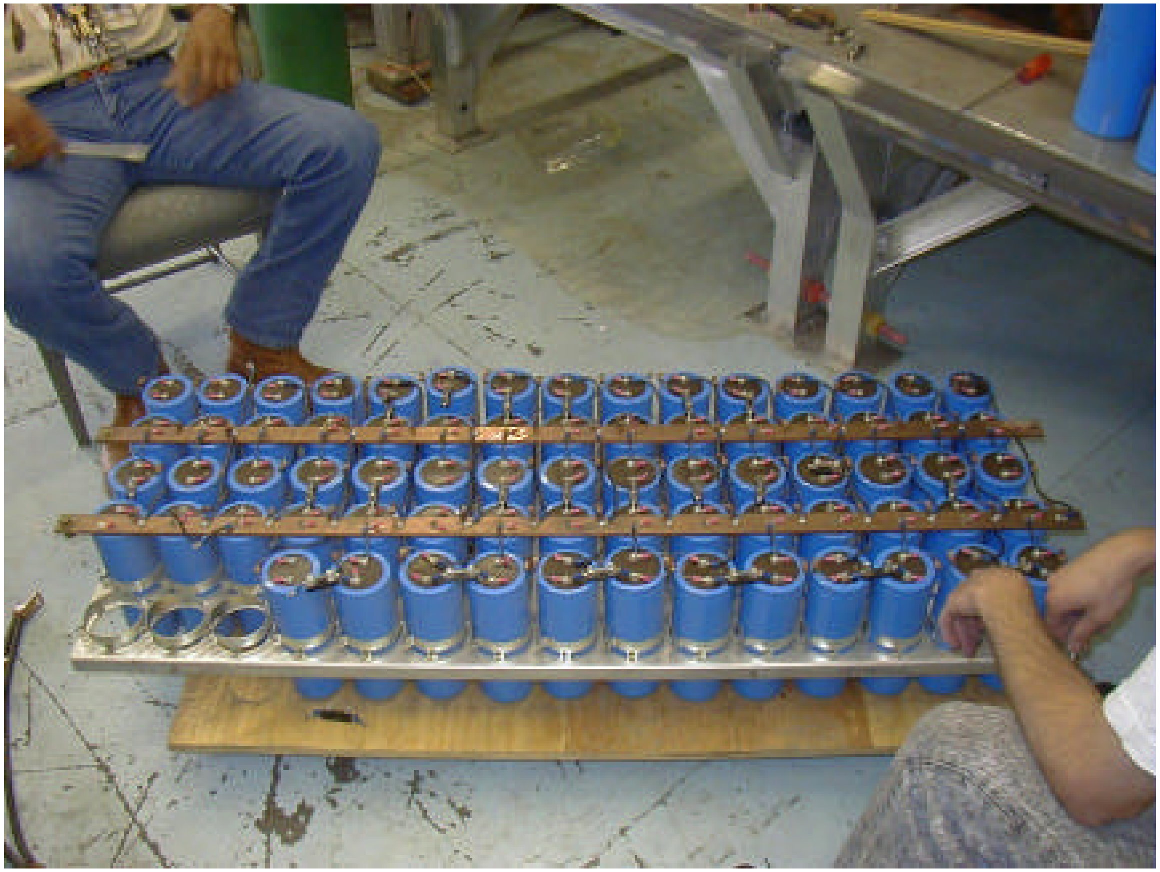
Power supplies for plasma guns on loan
from Univ Wisconsin

Student designed and built test & forming station for electrolytic capacitors



Test 12 caps at a crack

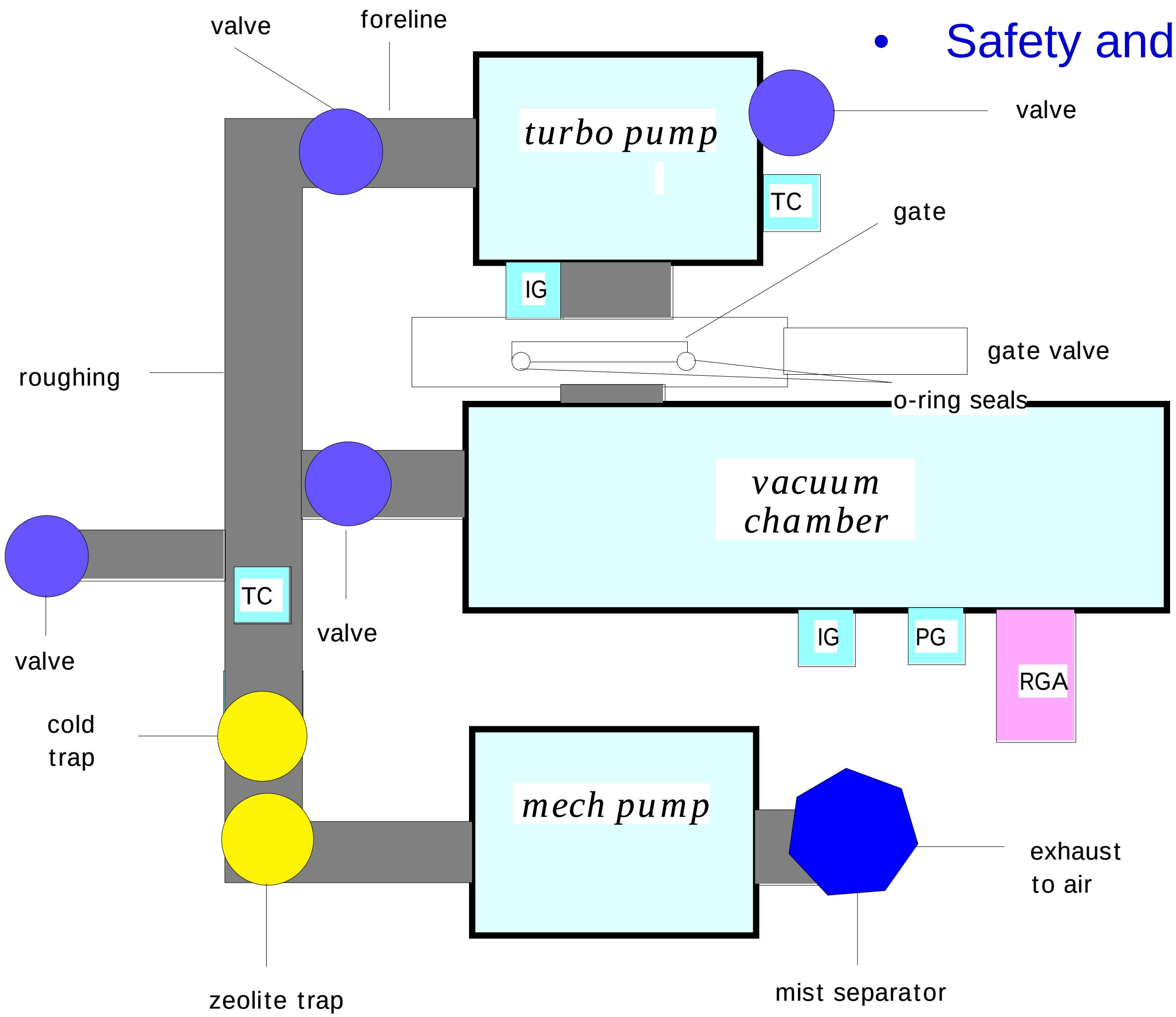
Two banks of electrolytics required like this



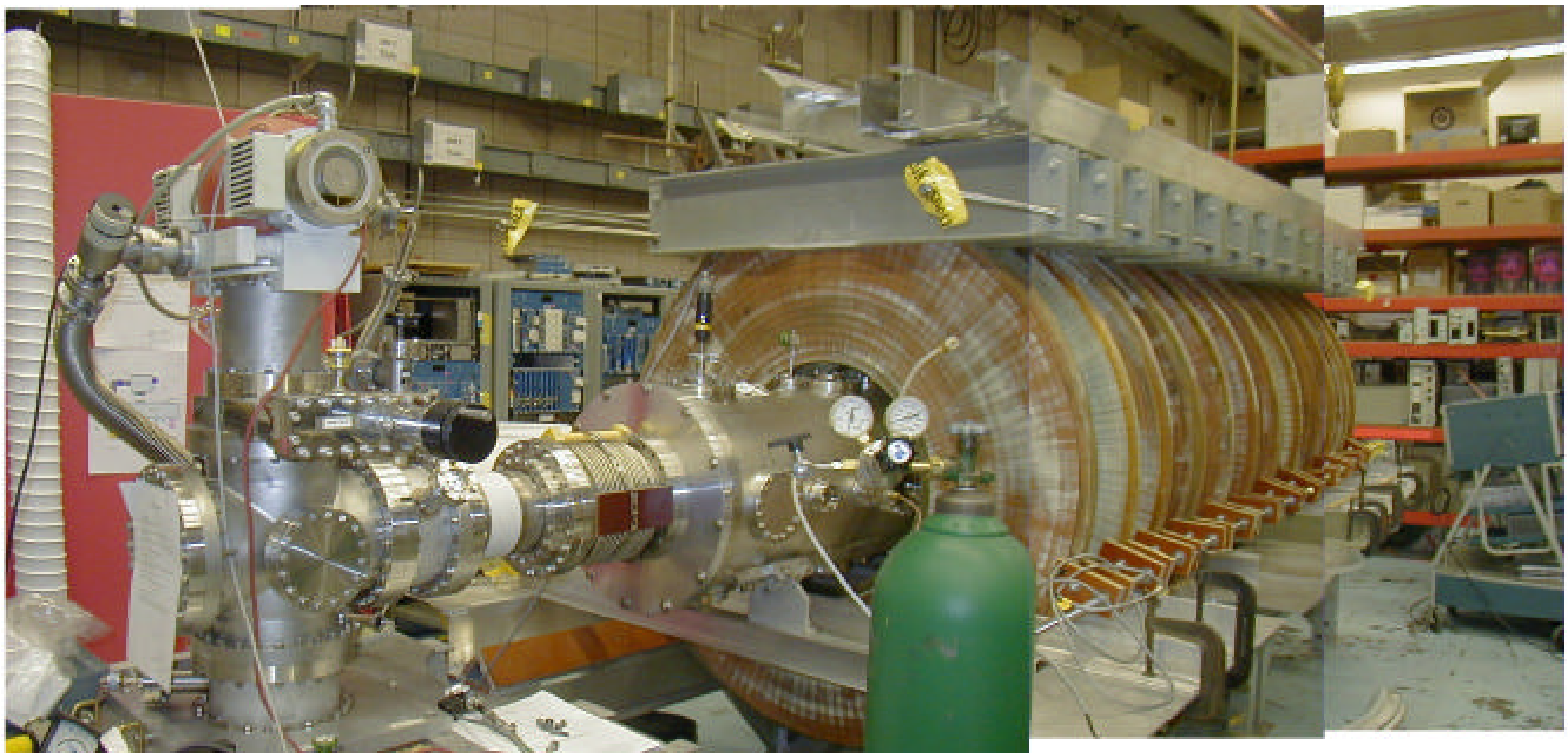
0.3 Farad @ 350 VDC, buswork to double the voltage

Student designed hardware

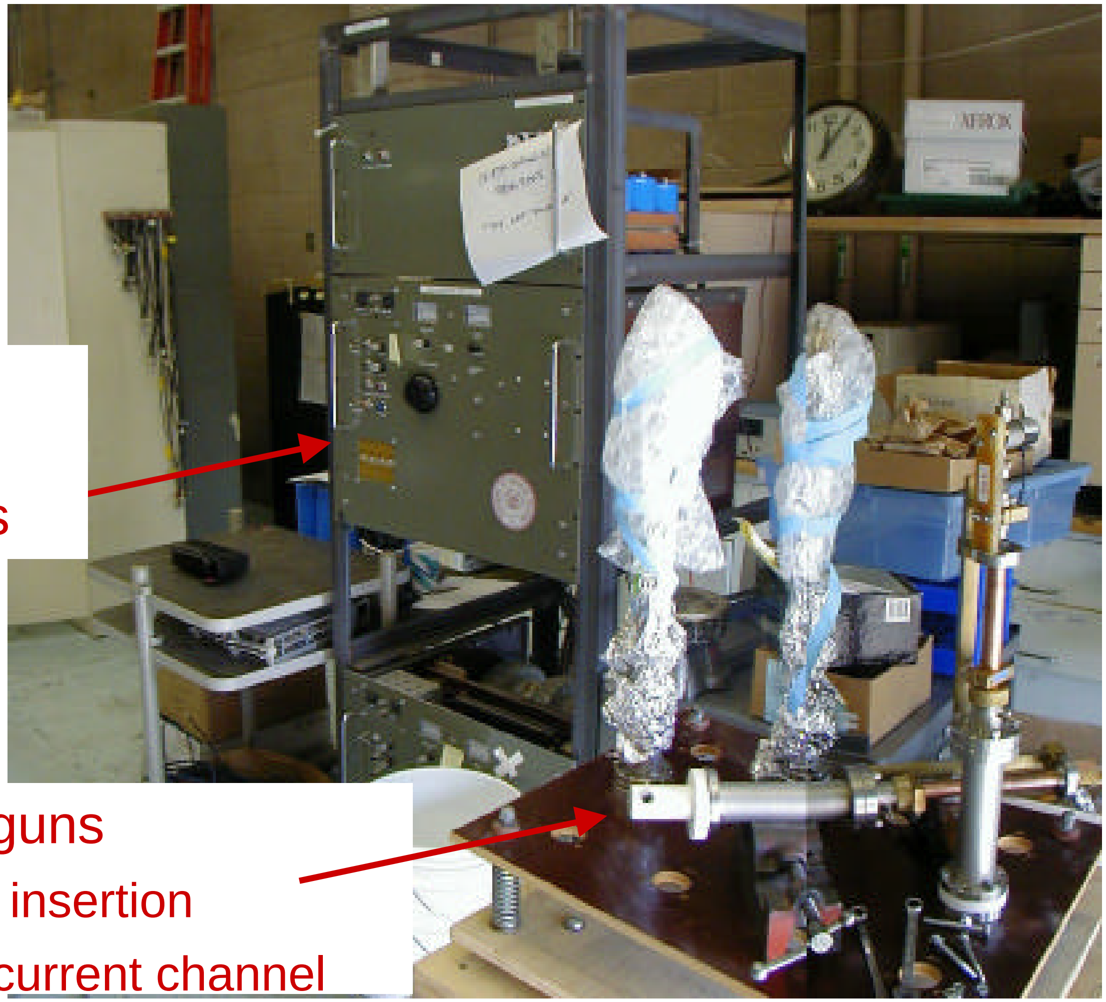
- Vacuum system
- Safety and fault interlock system



vacuum system stack



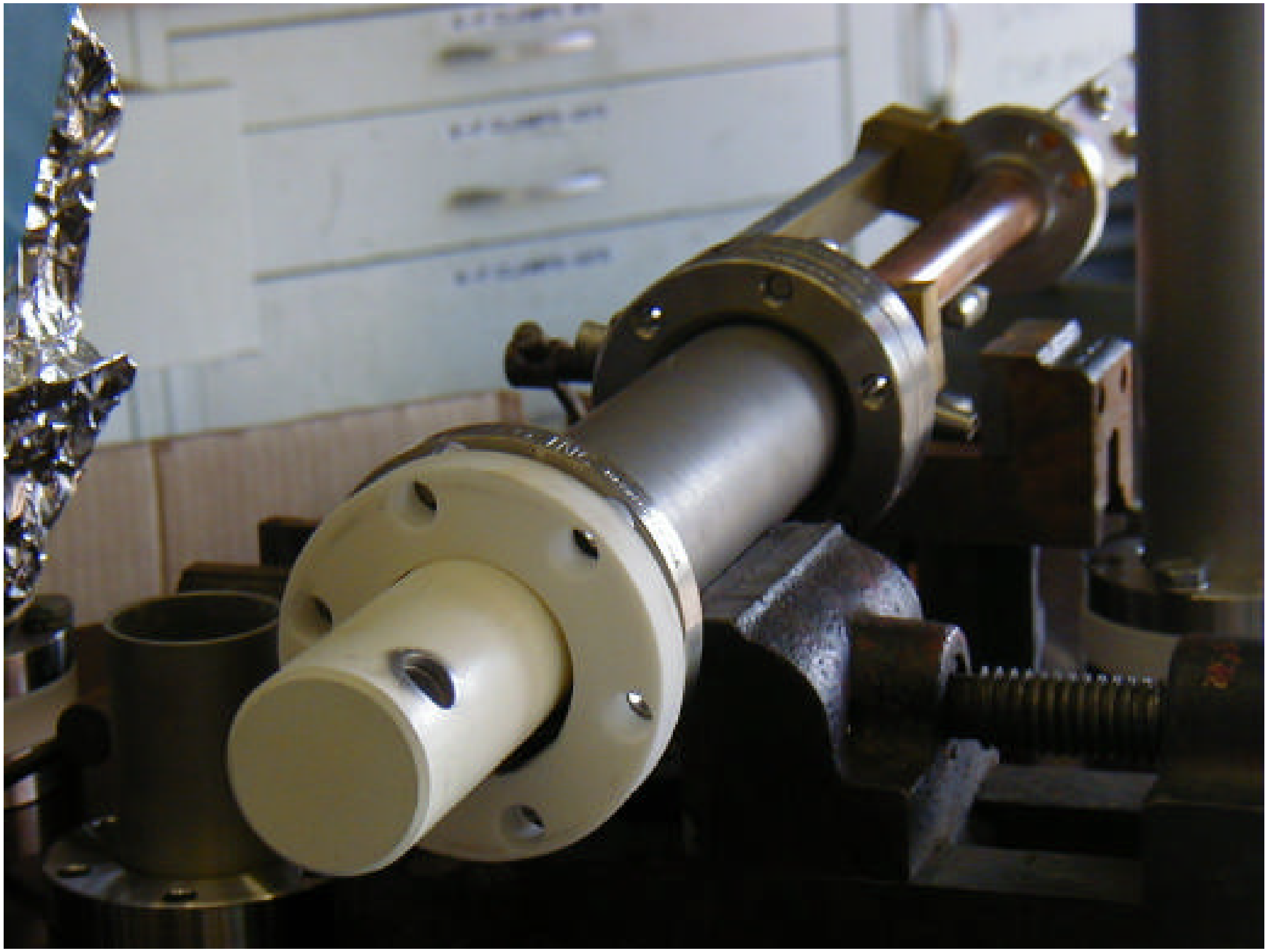
4 guns and 2 power supplies



2 power supplies with bias

- Plasma guns
  - radial insertion
  - axial current channel

radial gun insertion, axial aperture



Summary

- Design of RSX is complete
- Construction is nearly finished
- Experiments will come on line in late 2000
- We are *searching for a post doc* to lead the experimental effort!

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